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Experimental Analysis of the Development of Elastic Properties and Strength under Different Ambient Temperature during the Hardening of Concrete

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Abstract

This paper focuses on the experimental assessment of the degree to which continued exposure to low ambient temperatures influences the concrete modulus of elasticity and compressive strength. The elastic modulus is not a constant; in fact, it can reach very different values in concrete of the same strength class. It is thus important to have knowledge of aspects which have the greatest influence on it. One of the most important factors influencing the modulus of elasticity is the ambient temperature during concrete setting and hardening. The experiment tested the C 35/45 concrete, which was aged at temperatures of +20 °C, +10 °C and +5 °C. The result of the experiment is the determination of the modulus of elasticity and compressive strength in dependence on ambient temperature while comparing the obtained results with previously published findings.

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Keywords: Concrete; ambient temperature; modulus of elasticity; compressive strength

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1. Introduction

The modulus of elasticity is without a doubt one of the most important material properties of concrete, especially in terms of the design of new or the assessment of existing structures, which are susceptible to deformation [1,2]. The elastic modulus of concrete is rather variable. Concrete of the same strength class can reach completely different values as there is a broad spectrum of factors influencing it [3,4]. Apart from the composition, where the most substantial factors are the type, fraction and amount of aggregate, the w/c ratio and admixtures, especially air-entraining [5,6], the value of the elastic modulus is influenced mainly by the method and length of curing, water content and curing temperature [7,8,9,10,11]. The influence of temperature on the behaviour of concrete can be observed in several basic ways. It is possible to determine the changes in concrete properties as a result of temperature change, most commonly between -20 °C and +50 °C [12]. It is also possible to observe how the properties of concrete are impacted by its freezing, typically shortly after casting [13], or by exposure to high temperatures [14]. The development of the modulus of elasticity and compressive strength are also heavily influenced by the ambient temperature at which concrete sets and hardens. Most commonly encountered temperatures range from +10 °C to +50 °C. The values of the modulus of elasticity and compressive strength at an early age are linearly proportionate to ambient temperature. After a longer time, however, typically at the age of 28 days and more, concrete stored at lower temperature exhibits higher values of compressive strength [8,15]. This shows why it is necessary to understand how the development of basic concrete properties depends on temperature; especially when casting concrete at low ambient temperatures. During the first few days after casting, the value of the elastic modulus in particular is a decisive factor for correct prediction of the behaviour of more complex structures regarding their deformation [16]. Scientific publications [9,10,11,18,17] propose curves showing the dependence of the environment on compressive strength, while the minimum temperature is mostly +10 °C. However, these curves do not really correspond across publications. In fact, it appears the information is incomplete since, according to [18], the minimum temperature required for cement to hydrate is +5 °C and according to [19], hydration in fact stops below 0 °C. In addition, the development of the elastic modulus of concrete in dependence on ambient temperature is not addressed in these books. Nevertheless, according to [9] it progresses similarly to compressive strength.

2. Experiment

The goal of the experiment described herein is to determine the development of the elastic modulus and compressive strength of concrete which was aged at low temperatures. The development of the parameters was observed in concrete of the C 35/45 strength class setting and hardening at +20 °C according to [20] and at lower temperatures of +10 °C and +5 °C, when cement hydration is considerably slower. The dynamic modulus of elasticity was measured by means of the ultrasonic pulse velocity test using the instrument Pundit PL-200 from the Proceq company with 150 kHz probes, see Fig. 1 (a). The dynamic modulus of elasticity was identified as E_{cu} and was determined according to the standard [21]. The static compressive modulus of elasticity was determined using a testing press FORM+TEST ALPHA 3-3000 equipped with an electronic strain transducer, see [22]. The static modulus of elasticity was identified as E_c and was determined according to the procedure in [23], as shown in Fig. 1 (b). The bulk density of hardened concrete was 2 250 kg/m^3 with variation coefficient 0.6 %. Average cube compressive strength after 28 days of ageing was 77.3 N/mm^2 with variation coefficient 4.6 %.

The experiment determined the ambient-temperature dependence of the elastic modulus and compressive strength of a concrete used primarily for the manufacturing of pre-stressed bridge beams. Its composition is shown in Tab. 1. A total of 3 sets of prismatic specimens with the dimensions of 100 × 100 × 400 mm were made. Each set consisted of 18 specimens. Once cast, the prisms of the first set, identified as **t +20**, were stored in a laboratory at a temperature of (20 ± 2) °C and were covered with a PE foil. After 24 hours, the specimens were demoulded and stored in an environment of the same temperature of (20 ± 2) °C and relative humidity above 95 %. The prisms of the second set, designated **t +10,** were immediately after casting covered with a PE foil and stored in an environment with a temperature setting of +10 °C; specifically, it was a KD-20 automatic climate chamber. After 24 hours the specimens were demoulded, wrapped in PE foil and stored again at an ambient temperature of +10 °C.

The third set of specimens, identified as **t +5**, was treated similarly to the prisms of the **t +10** set; the only difference was the temperature setting of +5 °C.

Fig. 1. (a) Determination of the dynamic modulus of elasticity E_{cu} using the ultrasonic pulse velocity test; (b) determination of the static modulus of elasticity E_c.

Table 1. Formula of the C 35/45 concrete – data per 1 m^3 of fresh concrete.

Component	Amount [kg]
Cement CEM I 42.5 R	450
Sand 0-4 mm	690
Aggregate 4-8 mm	220
Aggregate 8-16 mm	845
Water	170
Plasticiser	4.50

Each time, three specimens from each set were tested at the age of 1, 2, 3, 7, 14 and 28 days. The first property to be tested was the dynamic modulus of elasticity E_{cu} followed by the modulus of elasticity in compression E_c. After that, the test prisms were subjected to destructive compressive strength tests. Compressive strength was identified as $f_{c,prism}$. The only exception were 1-day-old prisms from set **t +5**, the compressive strength of which was only 0.8 N/mm^2 and it was thus not possible to determine the static modulus of elasticity.

3. Results and discussion

The values of the dynamic modulus of elasticity E_{cu} are plotted against age and ambient temperature in Fig. 2. The most statistically significant deviations in the differences between the results were registered in the first few days of concrete aging. However, an age as young as 14 days already sees minimal differences between the values of the dynamic modulus of elasticity of concrete aging at different temperatures. Fig. 3 shows the values of the static modulus of elasticity E_c in dependence on age and ambient temperature. The trend of the development of the static modulus of elasticity closely copies the trend of the dynamic modulus. Again, the statistically most significant deviations of differences between the values can be seen in the first days of aging but become less pronounced at later ages. Fig. 4 shows the development of prism compressive strength in dependence on ambient temperature. The graphs show that the negative effect of ambient temperature is the most prominent in compressive strength and the least so in the dynamic modulus of elasticity, which can be clearly evaluated by comparing the 3-day values of the properties being observed. The average compressive strength of concrete that aged at +20 °C was 49.7 N/mm^2, while the concrete stored at +5 °C showed the value of 25.7 N/mm^2, which makes a difference of 48.4 %. The 3-day static modulus of elasticity of set **t +5** differed from **t +20** to a lesser extent, specifically by 25.9 % (30 000 N/mm^2 at +20 °C compared to 22 200 N/mm^2 at +5 °C) and in the dynamic modulus of elasticity, this difference was even smaller, i.e. 19.8 % (40 200 N/mm^2 compared to 32 200 N/mm^2).

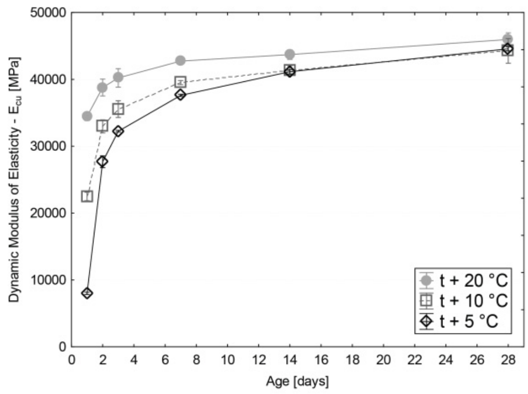

Fig. 2. Development of the dynamic modulus of elasticity of concrete over the first 28 days of aging in dependence on ambient temperature.

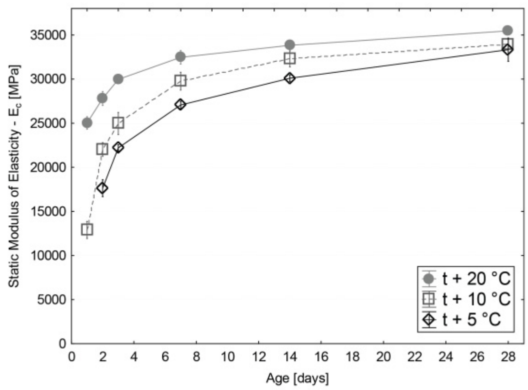

Fig. 3. Development of the static modulus of elasticity of concrete over the first 28 days of aging in dependence on ambient temperature.

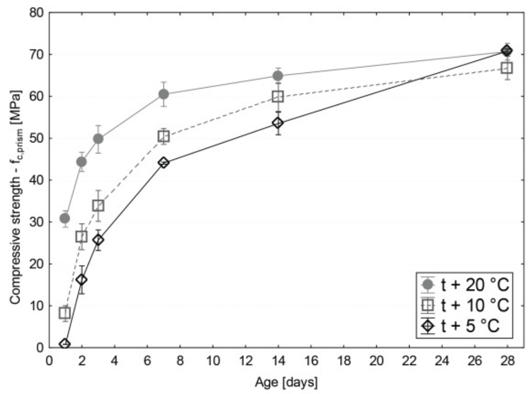

Fig. 4. Development of prism compressive strength of concrete over the first 28 days of aging in dependence on ambient temperature.

Fig. 5 (a) shows a relationship between the dynamic modulus of elasticity and compressive strength determined on the same specimen. A similar relationship for the static modulus of elasticity is shown in Fig. 5 (b). The obtained values show that the relationship between the compressive strength of concrete and its modulus of elasticity, whether static or dynamic, is not influenced by ambient temperature to any significant extent, which is in full agreement with the conclusions drawn in [9]. Furthermore, the obtained dependences of compressive strength on ambient temperature (Fig. 4) do not correspond to most theoretical curves presented in [10,11,15,17]. The most pronounced difference is observable in the behaviour of concrete at low temperature. While the theoretical curves show compressive strength at the temperature of +10 °C to be developing very slowly during the first few days, the experiment described herein registered a much steeper increase in compressive strength even at a temperature of only +5 °C. The reason can be the different strength class of the concrete – the books present theoretical curves for concretes of lower compressive strength than C35/45 concrete used in this research.

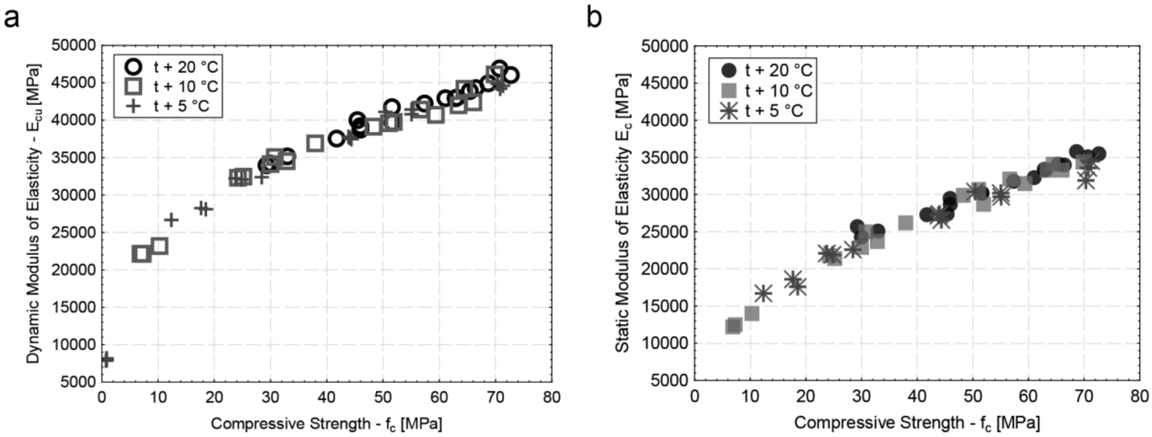

Fig. 5. (a) Dependence of the dynamic modulus of elasticity of concrete on its prism compressive strength; (b) dependence of the static modulus of elasticity of concrete on its prism compressive strength.

4. Conclusions

The following conclusions can be drawn from the results of the experiment described above.

- The development of the static modulus of elasticity and compressive strength of concrete is strongly influenced by ambient temperature, especially at an early age. During the first days, concrete aging at a lower temperature, particularly the concrete stored at +5 °C, exhibited very low values of the elastic modulus and compressive strength compared to concrete aging at +20 °C. The values of compressive strength and elastic modulus at the age of 28 days are not significantly influenced by ambient temperature.
- The negative influence of the environment, in which concrete is placed for the whole time of its setting and hardening, is most visible in compressive strength. After three days, the difference between concrete stored at +20 °C and concrete stored at +5 °C amounted to almost 50 %. The property least influenced by ambient temperature was the modulus of elasticity.
- The ambient temperature at which concrete ages does not have an influence on the relationship between its modulus of elasticity and compressive strength. This applies to both the static and dynamic modulus of elasticity.
- The observations of the development of compressive strength over the first 28 days of concrete aging in dependence on ambient temperature do not correspond to most theoretical curves published in the past [10,11,15,17].

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